

DUAL LIQUID FLYBACK BOOSTER FOR THE SPACE SHUTTLE

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ABSTRACT

Liquid Flyback Boosters provide an opportunity to improve shuttle safety, increase performance, and reduce operating costs. The objective of the LFBB study is to establish the viability of a LFBB configuration to integrate into the shuttle vehicle and meet the goals of the Space Shuttle upgrades program. The design of a technically viable LFBB must integrate into the shuttle vehicle with acceptable impacts to the vehicle elements, i.e. orbiter and external tank and the shuttle operations infrastructure. The LFBB must also be capable of autonomous return to the launch site. The smooth integration of the LFBB into the space shuttle vehicle and the ability of the LFBB to fly back to the launch site are not mutually compatible capabilities. LFBB wing configurations optimized for ascent must also provide flight quality during the powered return back to the launch site. This paper will focus on the core booster design and ascent performance. A companion paper, "Conceptual Design for a Space Shuttle Liquid Flyback Booster" will focus on the flyback system design and performance. The LFBB study developed design and aerodynamic data to demonstrate the viability of a dual booster configuration to meet the shuttle upgrade goals, i.e. enhanced safety, improved performance and reduced operations costs.

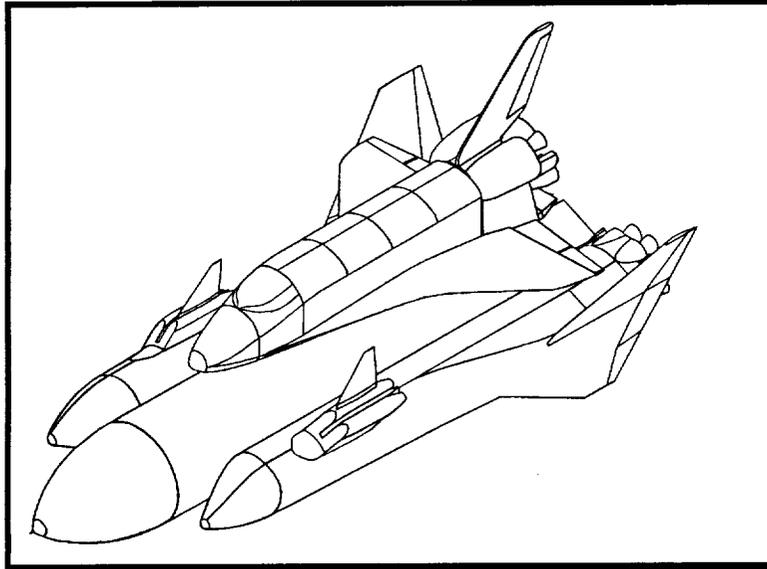


Figure 1 - Space Transportation System with Orbiter, External Tank, and Dual LFBBs - Ascent Configuration

INTRODUCTION

The concept of a flyback booster is not new. In the late '60s through the early '70s, NASA issued Phase A and B contracts to industry to create concepts for a fully reusable Two-Stage-To-Orbit (TSTO) Vehicle for the Shuttle Transportation System (STS). Original concepts utilized a manned flyback booster for the first stage. "All of the concepts presented by the contractors would have been expensive and contained large developments risks." (Reference 5). With NASA facing budget cuts in 1971 and receiving scrutiny of its fully reusable TSTO goals, the agency redirected its attention to lower costs for the STS by replacing the flyback booster with some sort of expendable stage. The selected booster configuration resulted with the Solid Rocket Booster as the 1st stage, a partially recoverable vehicle.

During the Access to Space Study performed in 1993, modifications to the current SRBs were addressed, as well as replacement boosters. Options included expendable liquid rocket boosters, hybrid boosters and flyback boosters. The flyback booster is now being revisited for study as an STS upgrade candidate. It is classified as a Phase IV upgrade, which is "... a major upgrade that significantly enhances system safety, reliability, supportability

or cost but requires significant configuration changes". (Reference 7). Dual LFBBs would replace the two SRBs currently attached to each side of the External Tank. (Figure 1)

Following are Tables 1 and 2, identifying LFBB program goals and a sampling of preliminary requirements the configuration must meet, respectively. Detailed Level II LFBB requirements are written in the Requirements Definition Document for the SSV / LFBB. (Reference 2)

<p>I. <u>Enhanced Safety and Abort Capability</u></p> <ul style="list-style-type: none">◆ Provide intact abort capabilities with partial or complete thrust loss from a single SSME engine◆ Eliminate Return to Launch Site (RTL) or Transoceanic Abort Landing (TAL) abort modes◆ Provide mission completion capability given a single booster engine out◆ Provide sufficient health monitoring avionics to accurately detect, identify, and take corrective action regarding engine performance anomalies◆ Incorporate reliability and safety in the design suitable for manned applications <p>II. <u>Enhanced Reusability and Reduced Recurring Costs</u></p> <ul style="list-style-type: none">◆ Low maintenance design with easy post-flight inspection and checkout to complement the fast turnaround and low recurring cost◆ Minimize modification to Orbiter, External Tank, launch and processing facilities <p>III. <u>Enhanced Shuttle Performance</u></p> <ul style="list-style-type: none">◆ Lift 40K lb payload (excl. 5K lb reserves) to 170 nmi at an inclination of 51.6 deg.◆ Optimize STS operation to extend operational life <p>IV. <u>Possible Government and Commercial Growth Paths</u></p> <ul style="list-style-type: none">◆ Identify alternate uses for the LFBB

Table 1 - Liquid Flyback Booster Program Goals

<ul style="list-style-type: none">◆ Shall be designed for use with the STS◆ Shall employ ascent trajectories that stay within the most demanding of either the current Shuttle ascent constraints or those defined by the STS integration team◆ Shall operate in an unmanned configuration◆ Shall return to launch site for runway recovery or an economically and operationally viable alternative◆ Shall flyback and autonomously land◆ Shall maintain or improve Orbiter abort capability◆ Shall utilize the Orbiter for ascent guidance; flyback guidance begins after separation◆ Shall have the ability for engine throttling to alleviate aerodynamic and structural load on the vehicle during ascent
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Table 2 - Preliminary Liquid Flyback Booster Requirements

RESULTS AND DISCUSSION

CORE BOOSTER DEFINITION

Baseline LFBB Configuration. The baseline dual LFBB configuration (Figure 2) was established to demonstrate technical viability with respect to mission performance and STS impacts and to provide a baseline for mass properties, cost, and schedule. The engineering baseline includes:

- 16.2 ft diameter, 152.1 ft long LOX/RP1 core booster
- 54° sweep angle delta wing
- Four air-breathing fly back engines (FBE)
- Four LOX-RP booster main engines (BME).

Flyback systems including wing configurations and FBEs are discussed in the companion paper, "Conceptual Design for a Space Shuttle Liquid Flyback Booster". (Reference 1). There are three candidate BME LOX-RP engines under consideration for the LFBB - - - Pratt & Whitney RD-180S, Aerojet AJ-800 and Rocketdyne RS-76. These engines are discussed further in the **ASCENT PERFORMANCE** Section.

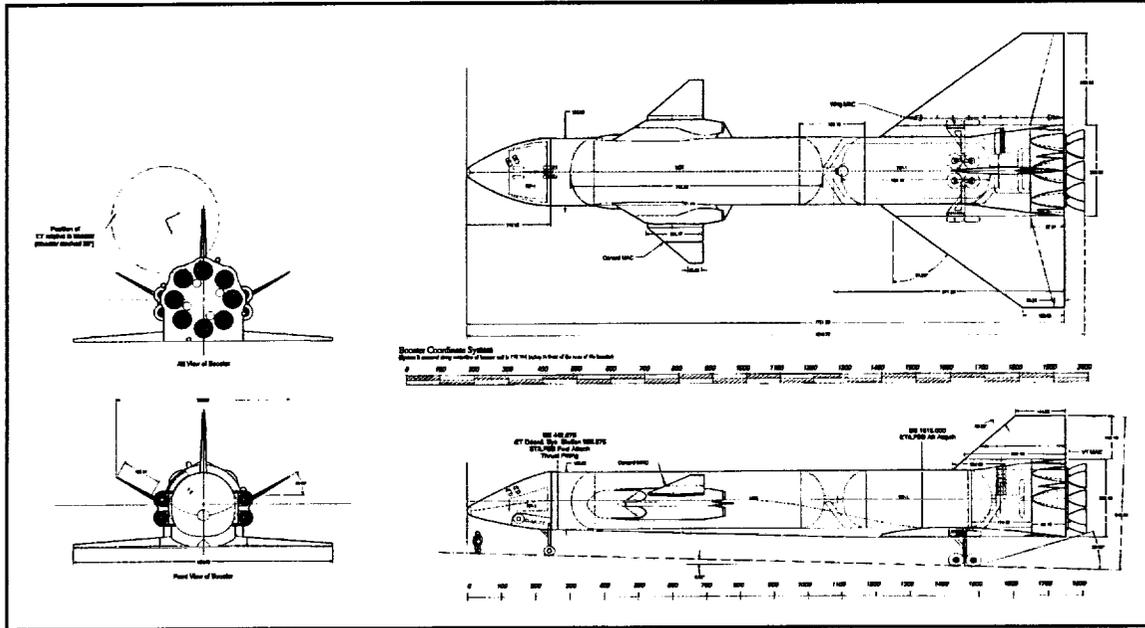


Figure 2 - Engineering Baseline Dual LFBB Configuration

Core Booster Design. The LFBB core booster serves as the structural backbone of the LFBB, interfacing with LFBB flyback systems and MPS, with the Shuttle External Tank (ET), and with the Shuttle Mobile Launch Pad (MLP). The 16.2 ft diameter core booster was baselined for engineering study (Figure 3). Preliminary booster configurations of 16.5 ft diameter and 16.8 ft diameter were developed for ascent performance analysis to support intact abort capability studies and are discussed in the **ASCENT PERFORMANCE** Section.

The 16.2 ft booster was designed to contain 1.1 million lbs of propellant in its tankage (a derived requirement to provide enhanced STS performance of 40K lb payload to orbit), to sustain vehicle bending and inertia loads under liftoff, ascent, and flyback load regimes, to provide structural interface to LFBB flyback and MPS systems and, to integrate with existing STS elements including the ET and the launch facilities with minimum and acceptable impacts to the STS vehicle and launch operations.

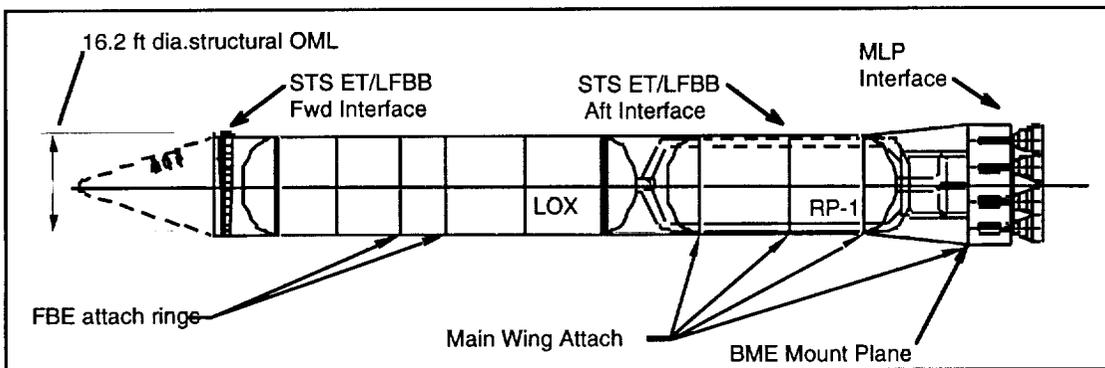


Figure 3 - Dual LFBB Core Booster

The aft thrust structure or boattail configuration is designed to support the BME under nominal and required engine out thrust conditions. The boattail configuration is optimized to reduce aerodynamic drag while maintaining an acceptable foot print for MLP interface and STS stiffness requirements. Design concepts were generated for the three BME candidates. See Figure 4. The candidate engines have significantly different packaging and support configurations resulting in delta thrust structure configurations, all of which can be designed to meet LFBB requirements.

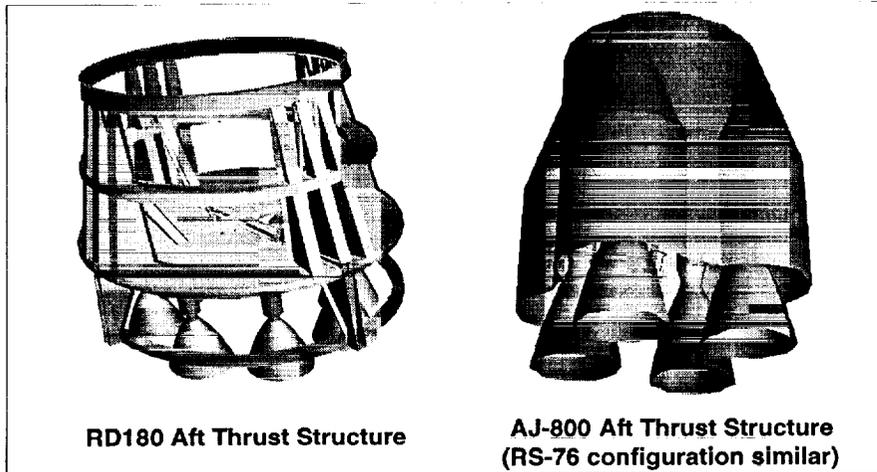


Figure 4 - Booster Aft Thrust Structure Configurations

STS Stiffness Impact Assessments. The dual LFBB configuration was designed to minimize shuttle system impacts. Specifically, core booster stiffness was designed to minimize impacts to launch operations under prelaunch and liftoff conditions and to minimize impacts to orbiter controls under ascent conditions.

SSME ignition on the launch pad causes the vehicle to 'pitchover' or bend about the LFBB hold-downs and build up strain energy. Excursions of the vehicle on the pad resulting from this motion, 'Z excursions', are key to launch facility impacts and liftoff sequence. Minimizing strain energy is critical to Shuttle liftoff loads. Launch sequence is dependent on SSME and LFBB ignition timing and ideally results in liftoff at the point of minimum strain energy or minimum 'Z excursion'. This base bending moment is primarily governed by LFBB stiffness and specifically by the LFBB aft thrust structure and hold-down configurations. In addition, release of cryo-induced loads at liftoff results in a dynamic 'Twang' response in the shuttle system. Orbiter controls and interface loads during ascent are influenced by overall booster stiffness.

A transient liftoff analysis was performed to verify LFBB and aft thrust structure stiffness at liftoff and to support the STS interface loads assessments. The LFBB finite element model (FEM) was coupled with existing ET and shuttle component stiffness models to perform a preliminary STS/LFBB transient launch pad stiffness assessment. The analysis indicates that LFBB stiffness is sufficient during liftoff and is equal to or exceeds SRB stiffness in the aft thrust structure region. The analysis indicates an LFBB/STS launch sequence similar to the SRB/STS launch sequence. See Chart 1 below. The 'Z excursions' during SSME thrust buildup are less than and similar to current excursions and well below the 20" limit stated in ICD-2-0A002. An LFBB stiffness similar to that of the SRB is an indicator of minimal impact to orbiter controls. Further shuttle system analysis is required to quantify any impacts.

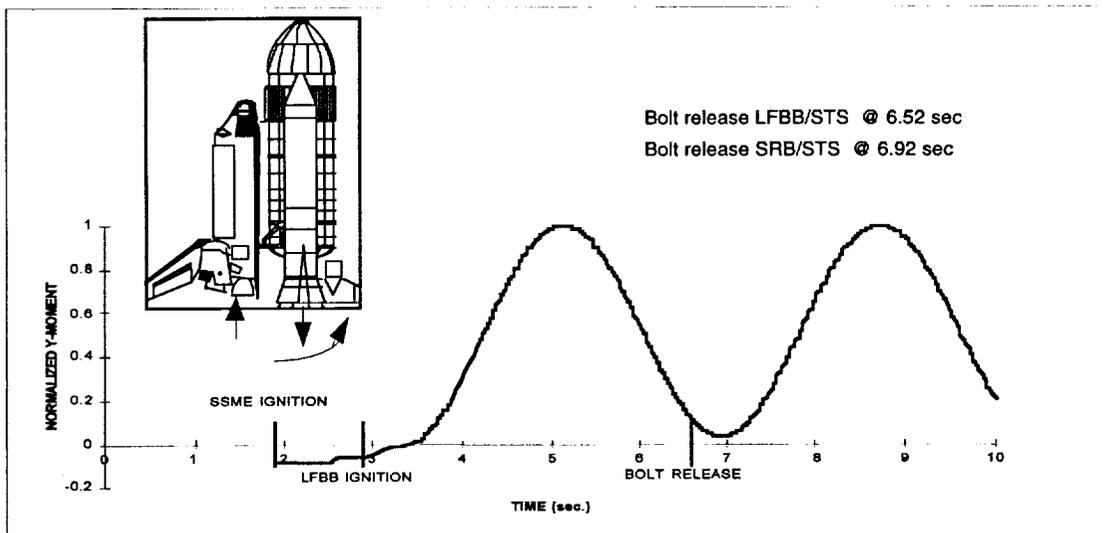


Chart 1 - LFBB/STS Transient Launch Analysis Results - Launch Sequence

Booster /ET interface loads and ET LOX tank pressures are higher at liftoff for the STS/LFBB configuration but maximum limits were not exceeded. The LFBB model was provided to the STS Integration Contractor to support further STS loads analysis.

In summary, the dual LFBB core booster configuration is shown to be similar to the current SRB configuration with respect to interface constraints, load paths, and stiffness and preliminary assessments indicate STS impacts to be minimized.

ASCENT PERFORMANCE

Ascent Constraints. A special Trajectory Design Data Package (TDDP) for the LFBB reference mission was created by the STS Integration Contractor. The data package defines Space Shuttle / LFBB system mission requirements, constraints and placards, and vehicle characteristics for the design of the first- and second-stage trajectories. (Reference 2). Specifically, the TDDP addresses:

- ◆Orbiter payload requirements
- ◆Insertion altitude
- ◆Orbiter vehicle and budgets (weight, non-propulsive consumables, ascent elevon schedule, landing weight, etc.)
- ◆SSME tag data (Block II, LOX/H₂ flowrates, nominal & abort power level, etc.)
- ◆BME performance / gimbal location data / ignition sequence
- ◆Main Propulsion System Budgets (LOX and H₂ tank ullage pressures, usable & unusable propellant mass, fuel bias, residuals, etc.)
- ◆Booster Propulsion System Budgets (LOX and RP usable and unusable propellant mass, etc.)
- ◆BME nominal throttling commands for liftoff, tower clear, max q, etc.
- ◆Separation conditions (for nominal and intact abort missions)
- ◆Nominal MECO conditions
- ◆SSME Power level (for nominal and intact abort missions)
- ◆ET Configuration
- ◆Generic Launch Date
- ◆Max Q & G constraints
- ◆Angle of Attack (Alpha Targets for Day of Launch I Loads Update (DOLILU) II PE
- ◆Angle of Sideslip (Beta Targets for Day of Launch I Loads Update (DOLILU) II PE

In addition to the TDDP constraints, there are constraints related to the ascent aerodynamic loads on the orbiter wing and ET/Booster forward attach points. Neither of these allowable design limits can be exceeded. Reference 1 addresses the effects of the LFBB wing design, control surfaces and angle of attack on the orbiter wing load during ascent.

Derived Ascent Performance Requirements. To meet preliminary program goals and LFBB requirements, certain booster-derived performance requirements were established. The engineering baseline booster, which is 16.2 ft in diameter requires 1.1 Mlb of usable propellant (794,444 - LOX, 305,556- RP) and approx. 3.6M lbf Vacuum thrust. Candidate LOX-RP engines must have vehicle health monitoring capability to control engine shutdown, thrust vector control capability with ± 8 deg. gimbal capabilities, etc.

Candidate engines for the LFBB program are the Pratt & Whitney RD-180S, Aerojet AJ-800 and Rocketdyne RS-76. (Figure 4) These engine options are considered to be within the same class of engines (providing 900-1000 lbf of vacuum thrust, 800-900 SL thrust) even though they vary significantly in many ways (i.e. weight, life, size, availability, booster integration, cost, gimbal rates, maintenance requirements, etc.). All are LOX-rich, staged combustion engines. All satisfy performance requirements with engine out capability, throttle to control "g and q" with the SSMEs at a constant 104.5% NPL, have engine health monitoring features and, package into an acceptable LFBB boattail envelope. In addition, all will require manned certification and verification. A paper listing selection criteria to aid in a future down-select engine for the LFBB program has been prepared for this JANNAF Propulsion Meeting. (Reference 4)

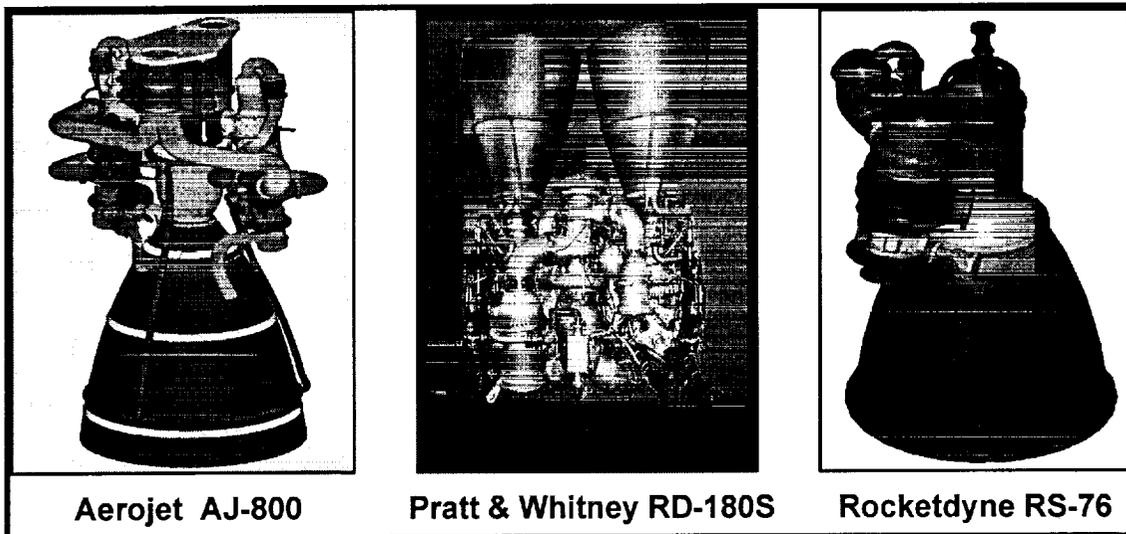
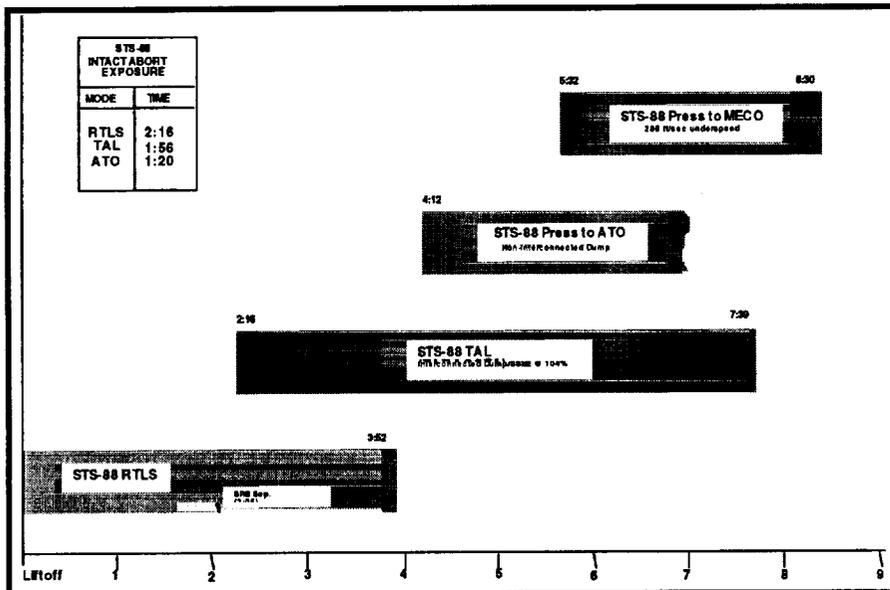


Figure 4 - Candidate LFBB Main Engines (BME)

Intact Abort Capability. While on the pad, the LFBB provides significant benefits over the current SRB. During start-up procedures, active LFBB Vehicle Health Monitoring can evaluate critical subsystem and structure conditions. Normal and anomaly situations can be assessed to provide timely decision-making and corrective actions, if needed. After SSME ignition then LFBB main engine ignition, VHM of the LFBB main engines will have the capability to assess any aberrations and signal any or all of the engines to be shut down. There is no intact abort capability once the SRBs have been ignited and prior to SRB separation.

Chart 2 below shows current STS intact abort capability with RTLS and TAL exposure.



RTLS exposure begins at liftoff. The first TAL opportunity is 2 minutes and 16 seconds Mission Elapsed Time (MET).

Chart 2 - STS-88 Intact Abort Windows

Charts 3 & 4 show enhanced intact abort capability with the LFBB, should an SSME fail during flight. Preliminary sizing assessments stemming from the 16.2 ft engineering baseline booster, show that a booster diameter of 16.5 ft will eliminate the TAL intact abort mode and a booster diameter of 16.8 ft. will eliminate RTLS or TAL intact abort modes.

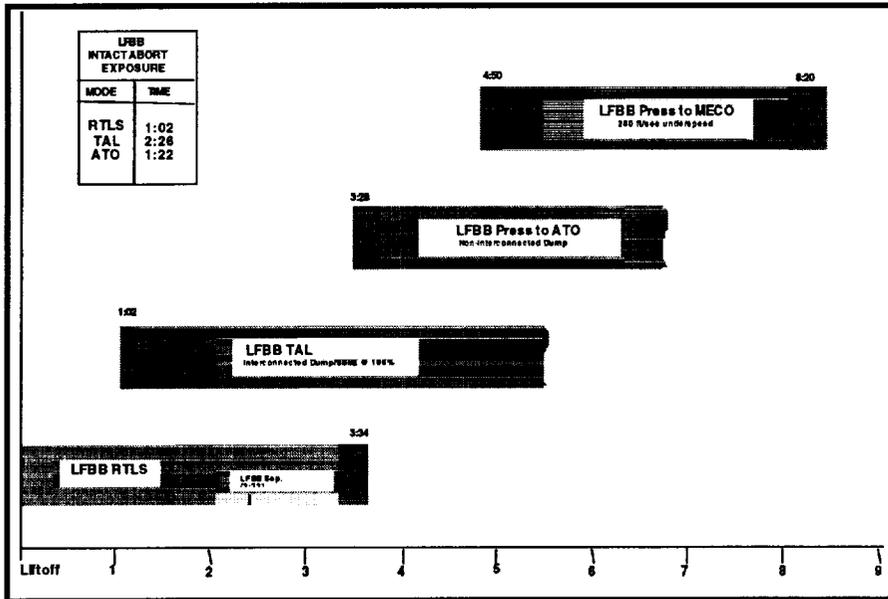


Chart 3 - Intact Abort Mode Windows with LFBB (16.5 ft. diameter - Eliminates TAL - "Preliminary")

Eliminate TAL:

Notice the overlap in MET at the end of the RTLS window and the beginning of the ATO window.

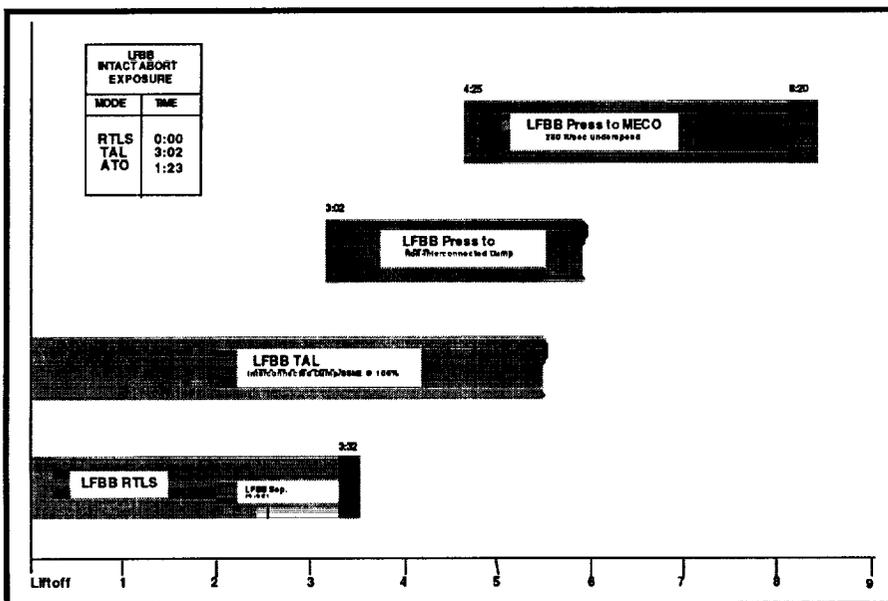


Chart 4 - Intact Abort Mode Windows with LFBB (16.8 ft. diameter - Eliminates RTLS or TAL - "Preliminary")

Eliminate TAL:

- ◆ RTLS exposure begins at liftoff.
- ◆ The end of the RTLS window overlaps the beginning of the ATO window.

OR

Eliminate RTLS:

- ◆ TAL exposure begins at liftoff.
- ◆ The end of the TAL window overlaps the beginning of the ATO window.

Ascent Performance. To meet the performance objective of mission completion with one booster main engine (BME) out and/or one Space Shuttle Main Engine (SSME) out, the LFBB is configured with 4 main engines. On the pad, or anytime during the 1st stage, if a booster main engine fails, there is ample performance margin in the other engines to enable a successful mission. The thrust level of the other engines on the same booster would be throttled up from 75% to 100% to reach nominal staging conditions. Engine VHM will have the capability to detect engine malfunctions and signal the orbiter to instantaneously command the BME shut down and throttle of the other engines. The loss of two engines - - - one on each LFBB achieves nominal mission success objectives. If an SSME fails, all LFBB engines would throttle from 75% to 80.7% to maintain required thrust levels to reach abort separation conditions.

Table 3 depicts LFBB performance variations resulting from requirements to either reduce TAL exposure, eliminate TAL or eliminate RTLS. LFBB usable propellant required to meet the objective drives the size of the configuration.

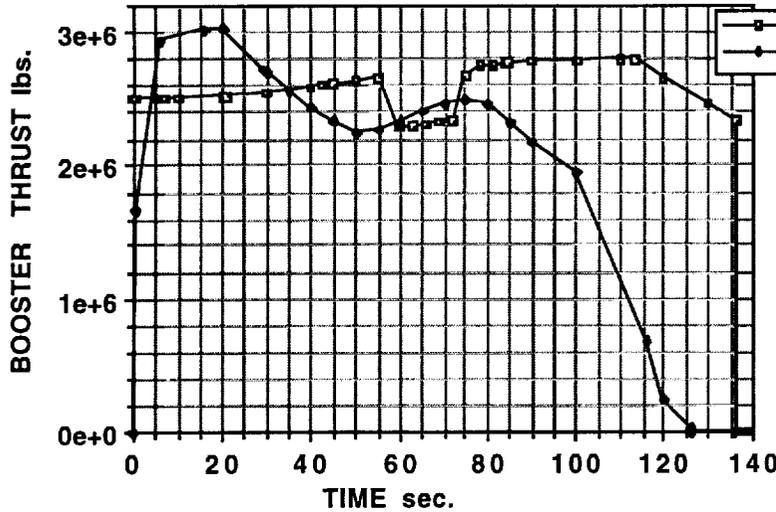
	"Reduce TAL Exposure" Configuration	"Eliminate TAL" Configuration	"Eliminate RTLS" Configuration
Payload / Development Reserve	40,000/4,600	43,600/5,000 lb	48,160/5,000 lb
Thrust / Weight @ T = 0	1.307	1.271	1.240
Max. Dynamic Pressure (Q)	685 psf	677 psf	697 psf
Burn Time	136 sec	142 sec	148 sec
Jettison Weight	546,344 lb	552,414 lb	553,042 lb
BME Engine-Out Capability	T=0 & make mission	T=0 & make mission	T = 0 & make mission
SSME Engine Out	Reduce TAL Exposure	Eliminate TAL	Eliminate RTLS
ET Configuration	LWT	LWT	LWT
Usable Propellant	1,100,000	1,160,000	1,220,000 lb
Booster Diameter	16.2 ft	16.5 ft	16.8 ft
Booster Length	152.1 ft	152.4 ft	152.7 ft
Booster Lift-Off Weight (BLOW)	1,373,172 lb	1,436,207 lb	1,496,521 lb
Gross Lift-Off Weight (GLOW)	4,680,000 lb	4,810,100 lb	4,935,946 lb

Table 3 - LFBB Performance Sensitivities to Intact Abort Requirements

The following table and charts are representative of the 16.2 ft diameter booster.

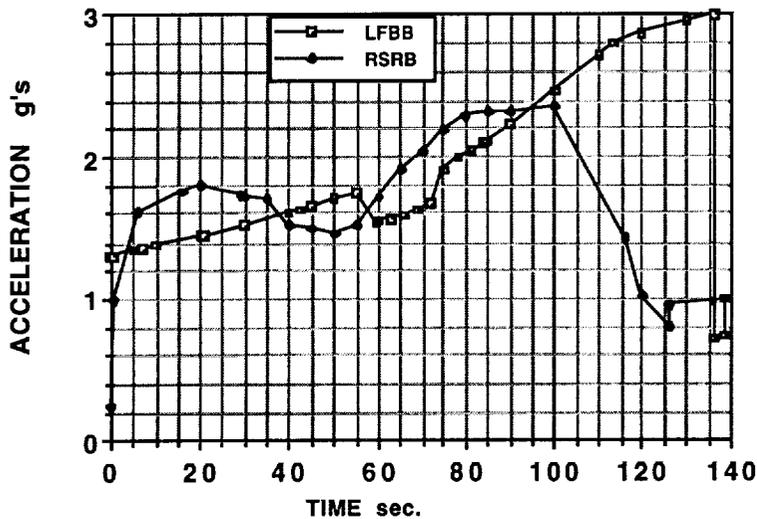
EVENT	TIME (sec)	WEIGHT (lbs)	REMARKS
Booster Engines @ NPL	0.00	1,373,172	Nominal Thrust Level is 75%
Lift-off	0.30	1,370,673	VHM Hold-Down
Single Axis Roll (SAR) Pitch Maneuver	7.00	1,314,860	14 sec pitch phase, linear to Alpha Profile
Begin Alpha Profile M = 0.6	42.39	1,020,034	USING LFBB TDDP Alpha profile
Begin Qmax Throttle-down	57.00	898,342	Throttle rate = 8.75 % /sec.
Max. Dynamic Pressure	71.00	797,331	QMAX = 685 psf, Mach # = 1.37
Begin Throttle-up	74.00	775,839	Throttle rate = 8.75 % /sec.
Mach Number = 2.5	94.46	609,945	STS Heating constraint Alpha = 2.0 until Sep.
FTB5 & 6 Throttling	113.36	448,668	ET Axial Load is more constraining, than 3 g's
Booster Engine Cut-Off	136.34	273,172	Instantaneous Booster Engine Shutdown
Booster Separation	138.74	273,172	Coast 2.4 sec.
SSME 3 G's Throttling	442.81	0	
SSME Cut-Off	494.05	0	30 x 170 NM Orbit @ 51.6 deg. inclination

Table 4 - Ascent Timeline



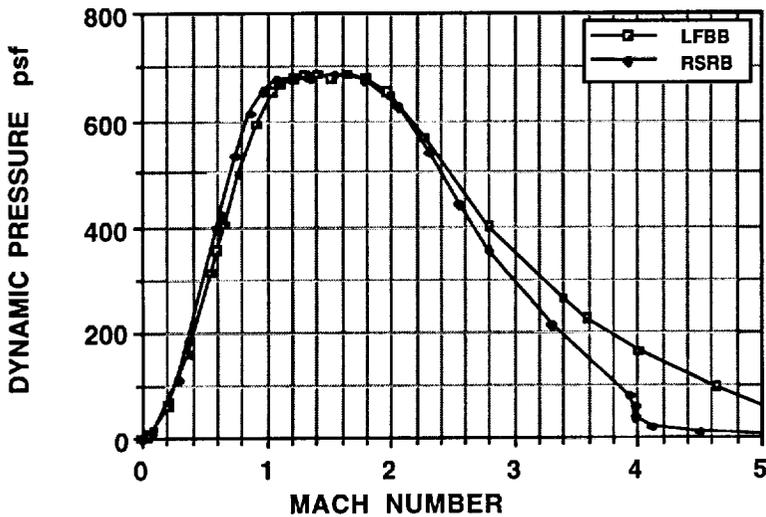
- Shows commanded throttle bucket for the LFBB; Required to not exceed the 1.6M lb ET/LFBB fwd attach load constraint
- SRB throttle schedule is designed into the propellant geometry
- LFBB eliminates SSME throttling during the 1st stage
- Burn time is longer with LFBB
- Thrust is more constant with LFBB

Chart 5 - LFBB Throttle Bucket



LFBB and SRB acceleration are bounded by the 3G limit constraint.

Chart 6 - Acceleration vs. Time



The LFBB trajectory is constrained by the Max Q limit of 685 psf at Mach 1.4 - 2.1 per the LFBB TDDP.

Chart 7 - Dynamic Pressure (Q) vs. Mach #

SUMMARY AND CONCLUSIONS

In addition to enhanced ascent performance and intact abort capability, the LFBB offers other program benefits. In comparison to the SRB, the LFBB provides increased safety. The LFBB is fully assembled upon arrival at the launch site, eliminating the potential for catastrophic energy release during SRB segment stacking and pre-launch preparations. Moreover, costly, precautionary measures to mitigate failure in all phases of SRB assembly, handling and transportation are eliminated. With onboard LFBB vehicle and engine health monitoring capabilities, an intact abort on the pad can be accomplished. The SRB cannot provide this function. Once the SRB motors are fired, they cannot be shut down on command. Safety is also achieved by the elimination of Crit 1 failure modes associated with SSME throttling at max q during the 1st stage. For a nominal mission, SSME thrust remains constant at 104%.

The LFBB increases shuttle and mission effectiveness. With the LFBB, the orbiter can carry 15,000 more pounds of payload to a space station elliptical orbit. The amount of payload is limited by the landing weight of the orbiter, not the LFBB. The LFBB can support polar capability from KSC and other potential DOD and commercial applications. Three flight sets support the STS in achieving 15 flights per year, with margin to support more, if needed. The LFBB is not on the critical path for pre-launch or turnaround operations. The LFBB BMEs operate in a normal mode at 75% thrust, providing performance margin. They can be shut down or throttled on command after ignition to terminate a mission on the pad or provide increased performance to complete the mission if one BME fails or supplement thrust if an SSME engine fails to facilitate an intact abort.

Being a fully recoverable vehicle which lands back to the launch site, the LFBB provides recurring cost benefits. Flight-to-flight analysis, checkout and reconfiguration is minimized. Preliminary pre-launch timeline comparisons for LFBB operations show a 20 day savings over current SRB operations. Less booster hardware will be inventoried. Sea recovery is not required, which eliminates significant SRB infrastructure support. Recurring cost estimates, showing significant reductions over current operations have been reported to NASA per contract requirements.

Another beneficial aspect of the LFBB is reduced hazardous emissions during ascent. The booster's effluents are environmentally friendly. Chemicals of environmental concern such as chlorine or aluminum oxide particles are not emitted into the air, as is the case with solid propellant rockets.

The dual LFBB configuration has been developed to integrate with the STS elements including the orbiter, ET and launch facilities with minimum and acceptable impacts to the STS vehicle and launch operations. Shuttle system impact studies show the resulting LFBB/STS configuration stiffness and constraints to be similar to the SRB/STS configuration indicating minimal and manageable impacts to launch sequence and operations and to STS elements.

Lastly, there are no technology break-throughs required to design or manufacture the LFBB vehicle. However, advanced development is required to mature the design concept and minimize program risk. Both hinge on joint, long-term commitments from the NASA, industry and other government agencies standing to gain great benefits from this program. Risk can be minimized by sharing the cost of development due to the many alternate LFBB usages that have been considered. The vehicle can provide a cost-effective, reusable alternative to conventional, expendable liquid or solid strap-on booster systems for first- and upper-stages. It can also function as a test bed vehicle for other development or Future X programs. Timely ground and flight demonstration programs would substantiate the design, help to qualify systems for flight readiness and certification, increase awareness and stimulate program advocacy. A stand-alone, sub-scaled flight demonstration vehicle is being considered as part of the LFBB program demonstration plan. In summary, preliminary assessments prove that the LFBB vehicle supports all of the shuttle upgrade program goals. "The LFBB concept is feasible, the benefits are significant, the demonstrator makes sense and the program merits advocacy". (Reference 6)

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